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Journal of the European Ceramic Society 23 (2003) 2387–2390

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Analysis of a high power ferrite differential phase shift circulator operating above ferrimagnetic resonance

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Abstract

Magnetic losses limit the power handling/frequency performance of all ferrite phase shift and control components. At high power levels nonlinear loss is prevalent but this can be avoided using a technique called 'mode segregation'. It is noted that this is achieved by biasing the ferrite above ferrimagnetic resonance. A combined magnetostatic/microwave finite element scheme is used to model this mode of operation in a differential phase shift structure used in air traffic control surveillance radars. Starting from the non-linear material magnetisation curve, the magnetic state of the ferrite is evaluated as a prerequisite to calculating the full microwave solution. Above resonance operation avoids nonlinear loss but this study indicates that the differential phase shift is reduced and larger magnetic bias fields are required. Calculations agree well with the experimental data.

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Keywords: Ferrites; Finite element calculations; Magnetic properties; Sensors; Thermal properties

1. Introduction

Ferrite phase shift and control components are present in most microwave systems.[1] Individual components range in size from the integrated MIC circulator on microstrip to cabinet size, water-cooled high power isolators in waveguide. The high power units are subsystems in their own right and present very challenging multi-physics design problems. All ferrite devices are limited by magnetic loss mechanisms, but at high power levels nonlinear loss, heating and the temperature dependence of the material's magnetisation must also be managed. Engineers are under pressure to produce new designs to meet specifications with improved power/frequency performance whilst driving down costs, weight and size.[2] Analytical and theoretical methods, which express data in terms of experimental variables, aid the design process by providing meaningful calculations, which can be directly related to measurements. This paper will outline a finite element procedure, which uses a magnetostatic solver to calculate the D.C. state of the ferrite prior to calculating the microwave characteristics. In this study, a low loss mode of operation is investigated for a differential phase shift (DPS) section used in air traffic control radar.

At high power levels, a nonlinear loss mechanism involving spinwave modes can arise in ferrite devices.[3] These rapidly varying plane waves are excited by thermal agitation and are supported by the vibration of electron spins in the crystal lattice. Under certain magnetic bias conditions energy is lost to spinwaves when the microwave field is above a critical value. Helszajn and Walker published a paper, which attempted to locate a low-loss region below ferrimagnetic resonance in order to manage this type of loss.[4] Using coupled mode theory to study the interaction between magnetostatic modes in the ferrite and the microwave signal, Weiner noted that there was a region of bias field, which avoided this nonlinear loss mechanism altogether.[5] In this region, the microwave energy is unable to couple into the spinwave mode spectrum. This effect is known as 'mode segregation' and is investigated here for a practical device. Weiner mode segregation is noted to correspond to bias fields above ferrimagnetic resonance.

When a microwave ferrite is externally biased, by either a magnet or an electromagnet, the ferrite produces a demagnetising field which is dependent on its shape. The so-called demagnetising factors for non-ellipsoidal ferrite cross sections has been extensively researched in the literature.[6–9] The magnetostatic solver circumvents this difficulty by calculating the spatial variation of the magnetic field and magnetisation throughout the ferrite.[10,11] This is an important

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doi:10.1016/S0955-2219(03)00152-3

development as low-field loss and nonlinear subsidiary resonance loss are both connected to bias field uniformity. The shape of the ferrite can be adjusted to improve uniformity and reduce loss.[11] The magnetostatic solution can be considered as a pre-processing step for the finite element microwave calculations. Once the signal frequency is specified the microwave tensor permeability entries can be evaluated. These are then input into a microwave formulation which calculates the phase shift for a given waveguide cross-section. The propagation constant for forward and reverse energy flow can be calculated and used to work out the differential phase shift. In this paper this is applied to the above resonance mode of operation where finite element (FE) calculations are demonstrated to agree well with the experimental data. Above resonance the differential phase is observed to be less with reduced symmetry in both the experiment and the calculations. However, this mode of operation is important for very high power applications where nonlinear losses associated with high temperatures and critical values of microwave field become unmanageable below resonance.

2. The differential phase shift circulator

High-power circulators are usually constructed using differential phase shift sections in rectangular waveguide.[1,4] The principle of operation is illustrated in Fig. 1. A signal incident at port 1 splits and arrives in phase at port 2 where it exits. A signal incident at port 2 arrives out of phase at port 1 and leaves at port 3. There are four ports altogether and the circulation direction is 1-2-3-4-1. The 180° differential phase shift is realised using ferrite loaded rectangular waveguide. A typical cross section is schematically illustrated in Fig. 2. The junctions at either end of the differential phase shift section can be constructed from 3dB hybrid couplers or folded hybrid T's. Each junction has its own phase characteristic, which must be included in the overall design.

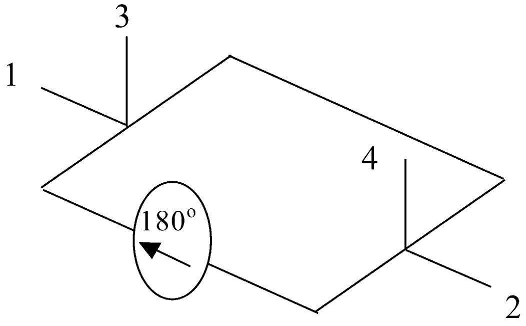

Fig. 1. A schematic diagram outlining the principal of operation of the 4-port differential phase shift circulator.

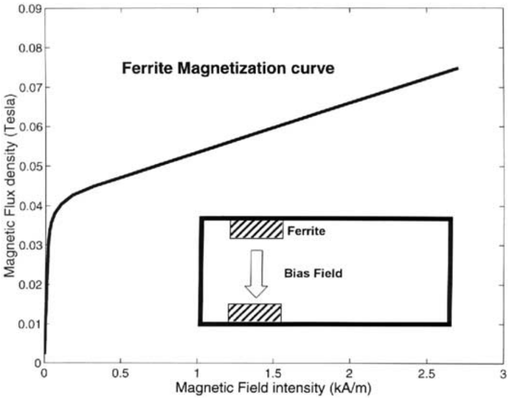

Fig. 2. The magnetisation curve for the ferrite material used in the DPS section. The cross section of the ferrite waveguide section is inset.

At high power levels, special precautions have to be taken in the design of microwave ferrite devices. For a given bandwidth, magnetic losses are a function of bias field. Three regions of loss must be avoided: low-field loss, nonlinear spinwave loss causing a subsidiary resonance, and ferrimagnetic damping resonance. Low-field loss is associated with the misalignment of the magnetic domains in the ferrite and occurs at low values of bias field, below saturation.[12] Nonlinear loss describes the coupling of high-power microwave fields to spinwave modes when the microwave field is above a critical value and the frequency/bias conditions permit coupling to the spinwave modes.[3] Resonance damping occurs when the microwave frequency and field polarity strongly couple to the precessional motion of the materials magnetisation.[13] It is of note that all of these loss mechanisms are avoided if the ferrite is biased above ferrimagnetic resonance. In Weiner's paper, he observed how the frequencies of the spinwave modes increased with applied bias field. At bias fields above ferrimagnetic resonance the electromagnetic mode is outside the spinwave spectrum and he called this 'mode-segregation'.[5]

3. Microwave formulation

A vector field analysis is required to solve ferrite-loaded waveguides as the propagating modes are generally hybrid. A suitable finite element formulation, which evaluates the propagation constant (β) as a function of the signal frequency (ω), permeability tensor entries (μ, κ) and the permittivity ($\varepsilon_o\ \varepsilon_r$) is implemented. It uses equations for the transverse electric (E_t) and magnetic (H_t) field components derived directly from Maxwell's equations. Integrating these equations over the waveguide cross section and applying appropriate boundary conditions for the waveguide electric wall yields the functional:[10,14]

$$F(\beta, E_t, H_t) = \int_s \Big[\omega\varepsilon |E_t|^2 + \omega\mu_o \Big(|H_x|^2 + \mu |H_y|^2 \Big) - \frac{1}{\omega\varepsilon} |\nabla_t \times H_t|^2 - \frac{1}{\omega\mu_o\mu} [\nabla_t \times E_t + \omega\mu_o\kappa \cdot H_x]^2 \Big] ds - \beta \int_S z \cdot \big[E_t^* \times H_t + E_t \times H_t^* \big] ds \qquad (1)$$

In this functional the permeability parameters are defined as follows: [13]

$$\mu = 1 + \frac{\gamma^2 HM}{\gamma^2 H^2 - \omega^2} \qquad (2)$$

$$\kappa = \frac{\gamma\omega M}{\gamma^2 H^2 - \omega^2} \qquad (3)$$

where, M is the material magnetisation, H is the internal bias field and γ is the gyromagnetic ratio. An FE solution of these equations is obtained by constructing a mesh over the waveguide cross-section. The discretised electric and magnetic fields within each element of the region are approximated using edge elements.[15]

4. Magnetostatic formulation

To evaluate the tensor entries accurately, the internal field and magnetisation within the ferrite must be known. The relationship between these values and the applied bias field is complicated by the effect of the demagnetising field due to the surface divergence of the magnetisation vector.[6–9] A magnetostatic finite element solution is used here to calculate the M and H variables directly.[10,11] A mesh is constructed over the full geometry including the ferrite-loaded waveguide, magnetic material and the bias circuitry. A magnetisation curve is used to characterise the nonlinear ferrite material and this is shown in Fig. 2. A standard two-dimensional FE magnetostatic solver is used to solve the nonlinear Poisson equation in terms of the axial component of the magnetic vector potential (ψ)

$$\nabla_t \cdot \left(\mu^{-1} \nabla_t \psi \right) = -J \qquad (4)$$

where J is the bias current density and μ^{-1} is described by the nonlinear magnetisation curve in Fig. 2. From ψ the internal flux density (B) and magnetic field (H) are derived before using the constitutive relation,

$$B = \mu H + M \qquad (5)$$

to find the magnetisation (M) of the ferrite. It is of note that B, M and H will vary spatially within the ferrite and this has been investigated in a previous publication.[11]

5. Results

This analysis has been applied to the differential phase shift section of a 4-port circulator used in an air traffic control radar system. The unit is water-cooled and has an operating bandwidth from 1.2 to 1.415 GHz, handles 250 kW peak power and 15 kW average power above resonance. The geometrical and material information has been applied to the magnetostatic solver to produce information about the magnetic state of the ferrite. This data was substituted into the microwave finite element solver to calculate the phase shift as a function of bias field. The operating frequency was set to 1.3 GHz. The bias field was swept through resonance to predict the propagational performance of the dominant mode above and below resonance. The phase constant plot is shown in Fig. 3 for the dominant mode. Below resonance the phase constant split is more symmetrical and greater than the corresponding split above resonance. The symmetry of split is related to bandwidth and below resonance operation is therefore selected for broader band applications. However, the above resonance modes lie outside the main loss regions as low field loss and nonlinear spinwave loss occur below the ferrimagnetic resonance region. The onset of low field loss depends on the value of saturation magnetisation and the demagnetisation factor. The nonlinear losses are prevalent at high power levels and biasing above resonance has the major advantage of avoiding these loss mechanisms. The region is consequently used for very high power applications where bandwidth is not so critical. Referring to Fig. 3, as the bias field increases through resonance the dominant mode reappears and Weiner called this point ‘mode segregation’. Care must be taken not to bias the mode too close to resonance as the resonance damping losses may dominate. The important parameter is the differential phase shift and this is compared with experiment in Fig. 4. There is good agreement between calculations and experimental

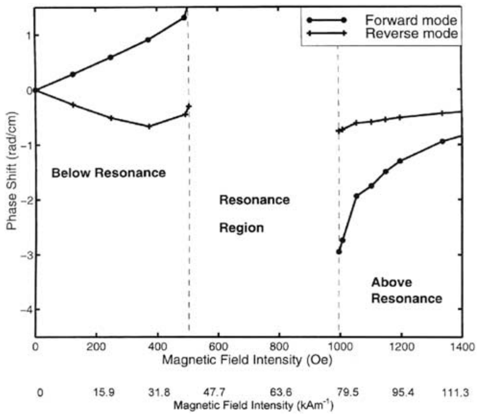

Fig. 3. Above and below resonance finite element calculated phase constants for the dominant mode in rectangular waveguide.

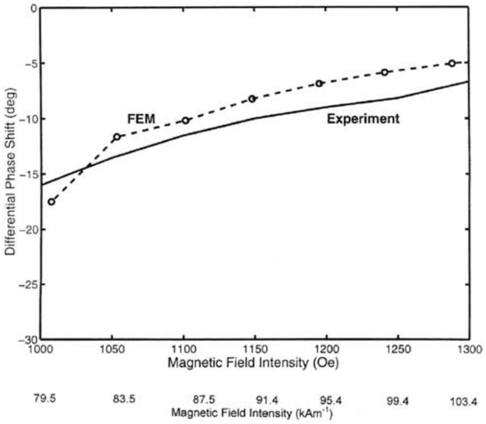

Fig. 4. Comparison of the finite element calculated differential phase shift with the experimental data for above resonance operation.

data. Larger bias magnets are evidently required above resonance but by using new materials such as neodymium, magnet assemblies are becoming more compact.

6. Conclusion

A combined magnetostatic/microwave finite element scheme has been implemented for microwave ferrites and used to model the low-loss mode of operation known as ‘mode segregation’. It has been noted that this corresponds to biasing the ferrite above ferrimagnetic resonance. The magnetostatic solver provides information about the magnetic state of the ferrite as a preprocessing step before the microwave calculations are performed. This avoids using any approximations about the demagnetising fields and permits calculations in terms of applied field and frequency, which directly relate to measured parameters. Below resonance operation is shown to be associated with symmetrical phase constant splitting but magnetic losses must be managed. Above resonance operation has less favourable differential phase shift characteristics but the important magnetic losses are avoided. The finite element calculated data for a differential phase shift section used in radar systems for air traffic control is shown to be in good agreement with the experimental measurements.

Acknowledgements

The authors would like to acknowledge the help and support of TRAK Microwave Ltd., Dundee, UK for providing the experimental data and the EPSRC for financial support through contract GR/L19737.

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